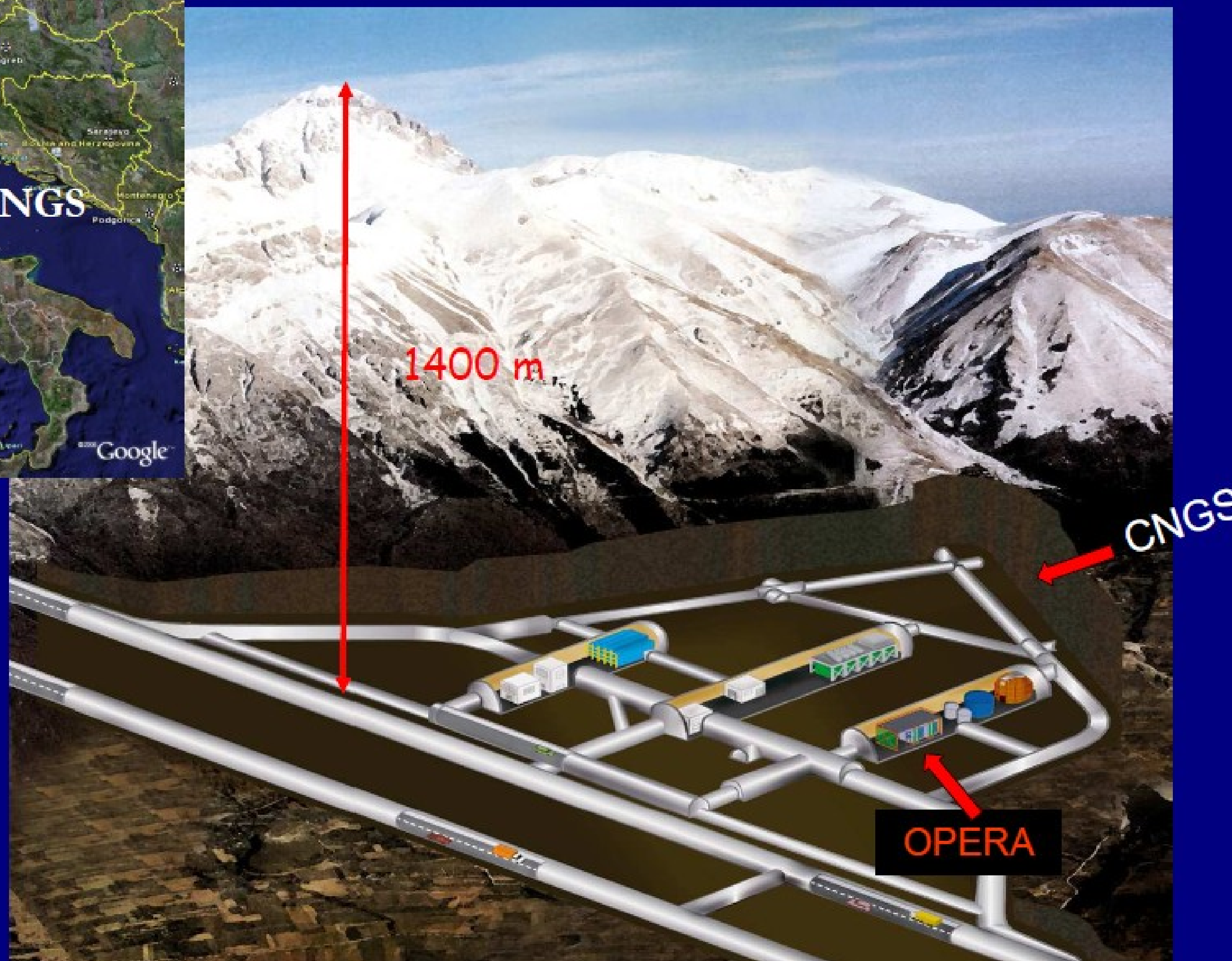
OPERA

Последние результаты

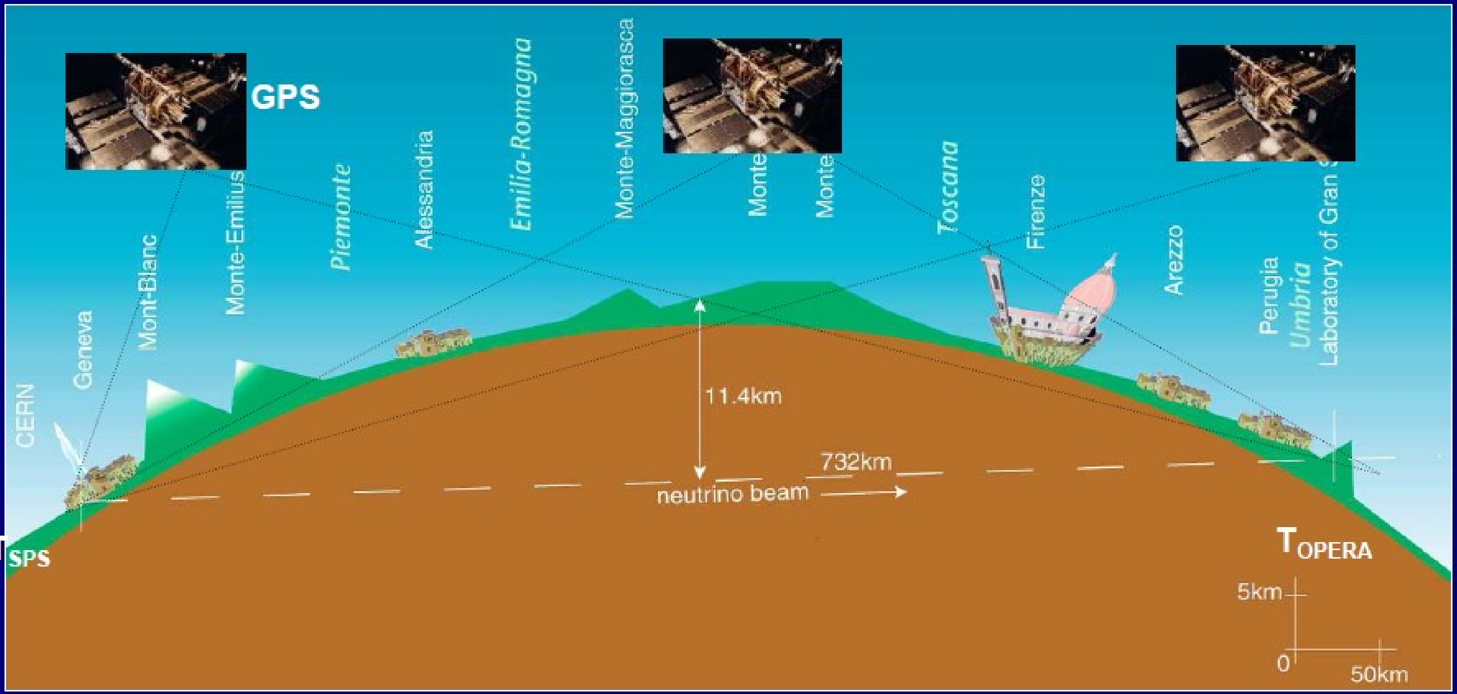
По материалам семинара в Церн

23 сентября 2011 г.

The LNGS underground physics laboratory



CNGS events selection



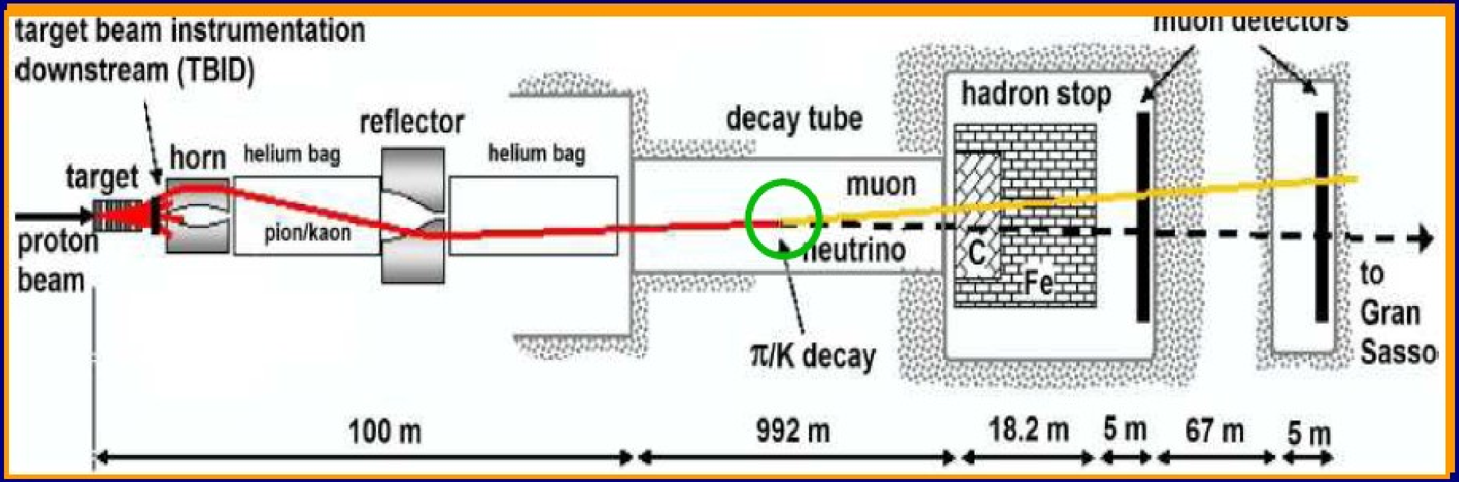
Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

$$|T_{OPERA} - (T_{Kicker} + TOFc)| < 20\ \mu s$$

Synchronisation with standard GPS systems ~100 ns (inadequate for our purposes)

Real time detection of neutrino interactions in target and in the rock surrounding OPERA

Neutrino production point



Unknown neutrino production point:

$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

1)accurate UTC time-stamp of protons
2)relativistic parent mesons (full FLUKA simulation)

TOF_c = assuming *c* from BCT to OPERA (2439280.9 ns)
TOF_{true} = accounting for speed of mesons down to decay point
$\Delta t = TOF_{true} - TOF_c$

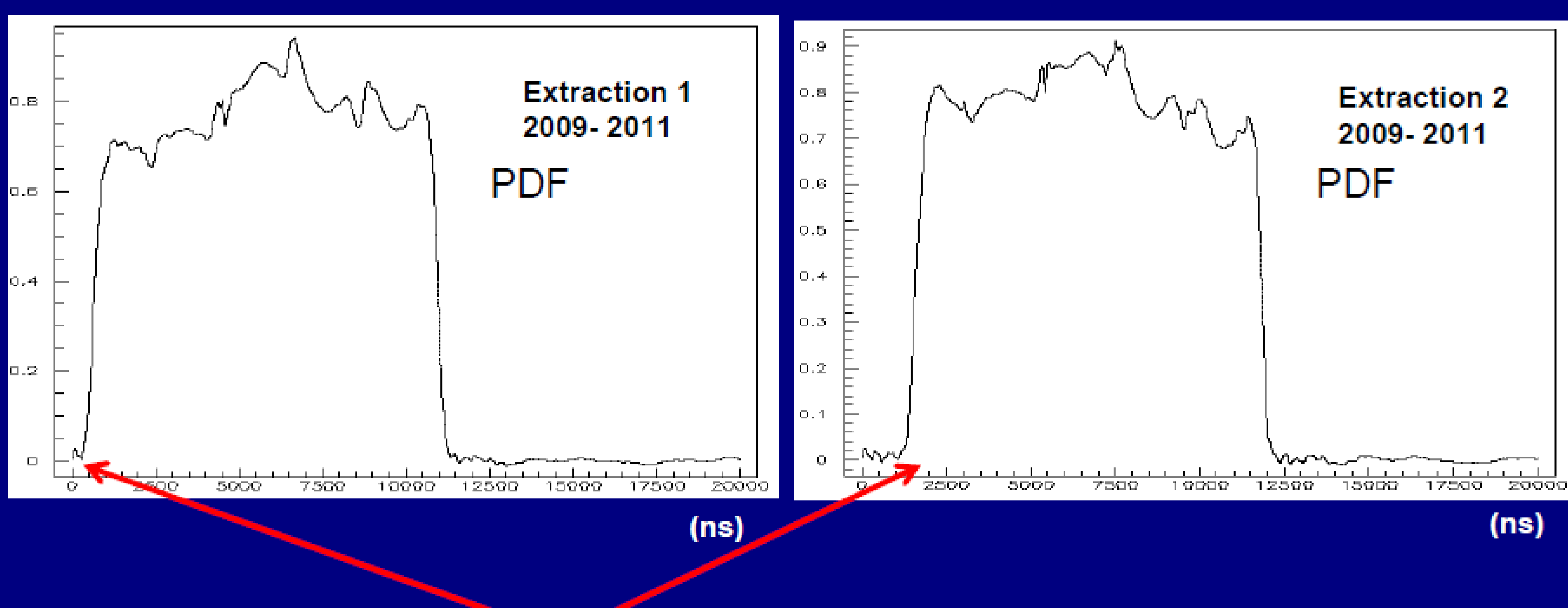
$\langle \Delta t \rangle = 1.4 \times 10^{-2}$ ns

Neutrino event-time distribution PDF

- Each event is associated to its proton spill waveform
- The "parent" proton is unknown within the 10.5 μs extraction time

→ normalized waveform sum: PDF of predicted time distribution of neutrino events

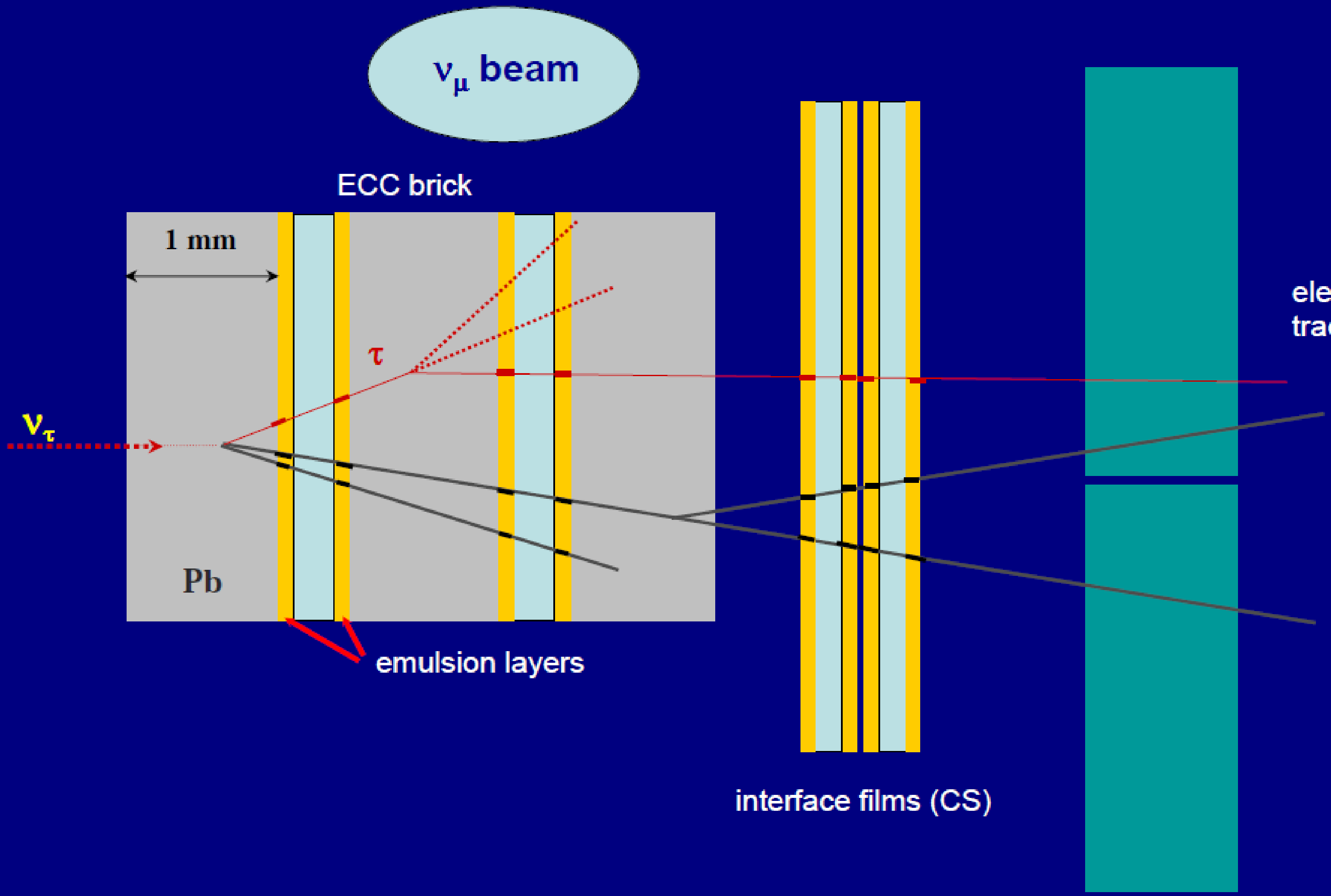
→ compare to OPERA detected neutrino events



different timing w.r.t. kicker magnet signal

THE DESIGN OF THE OPERA EXPERIMENT

ECC BRICKS + ELECTRONIC DETECTORS FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATION STUDIES



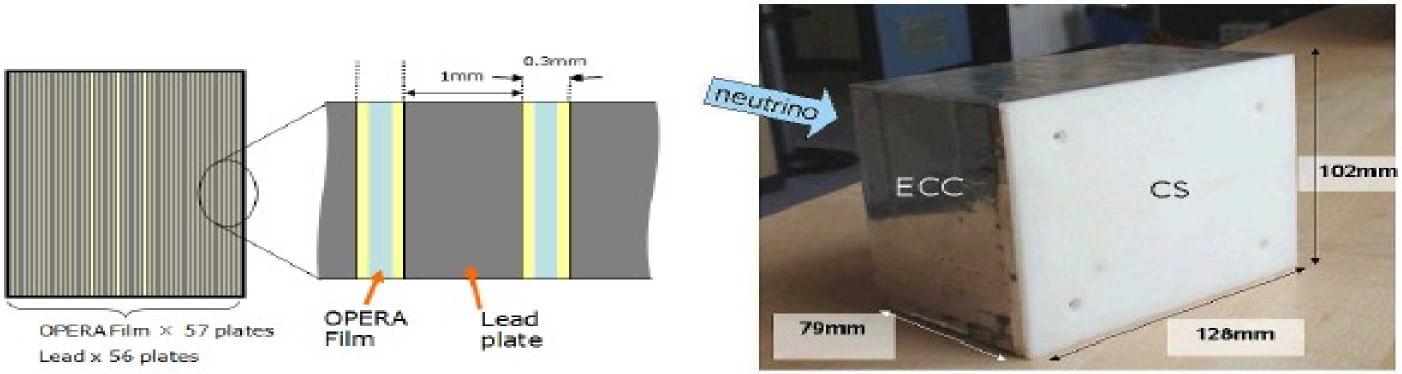


Figure 9. Left: schematic view of a brick in the target. Middle: blow-up insert showing two emulsion films and one lead plate. Right: photograph of a real brick as produced and inserted in the OPERA walls; CS is the box containing the two Changeable Sheets.

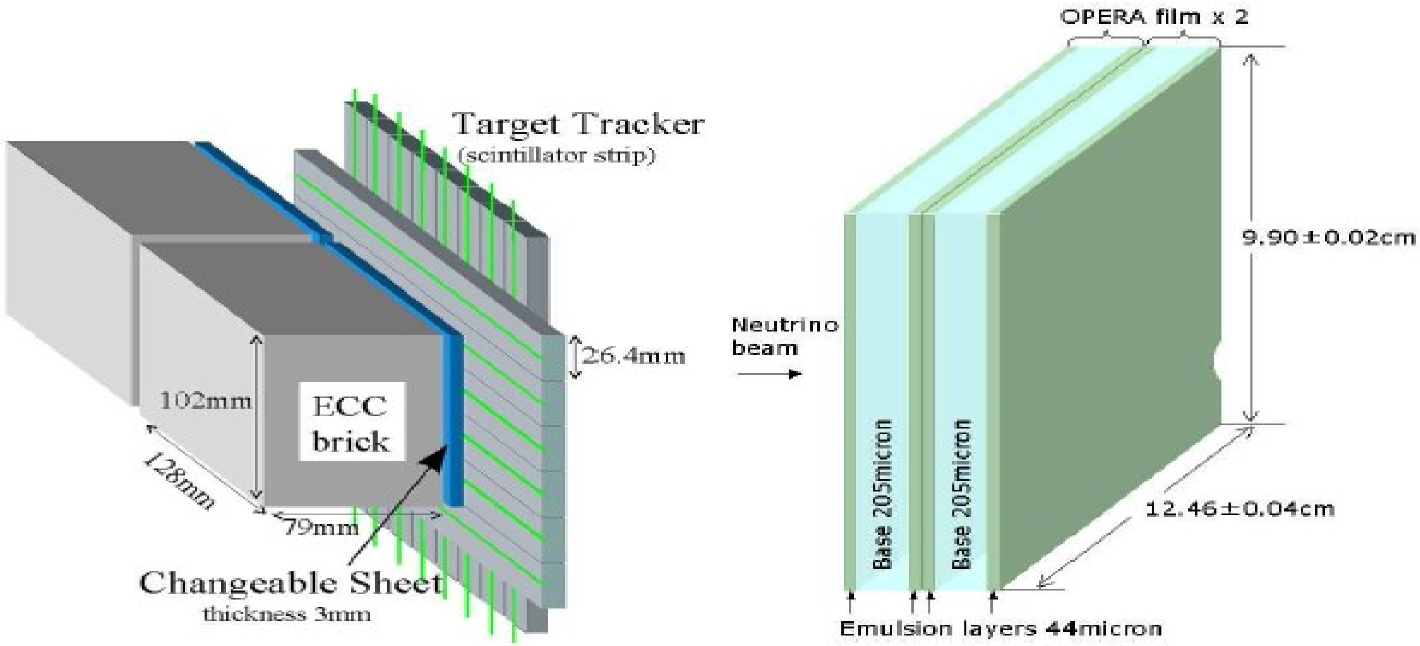


Figure 10. Schematic view of the brick with the Changeable Sheets in the target (left) and of the Changeable Sheet doublet (right).

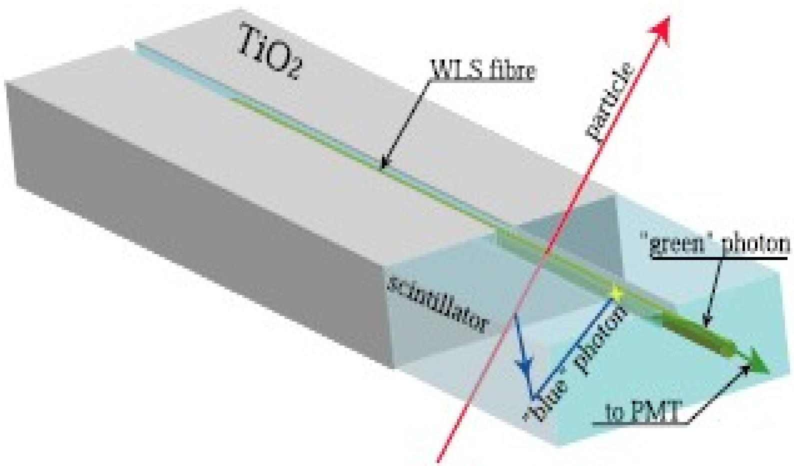


Figure 19. Schematic view of a scintillator strip with the WLS fiber.

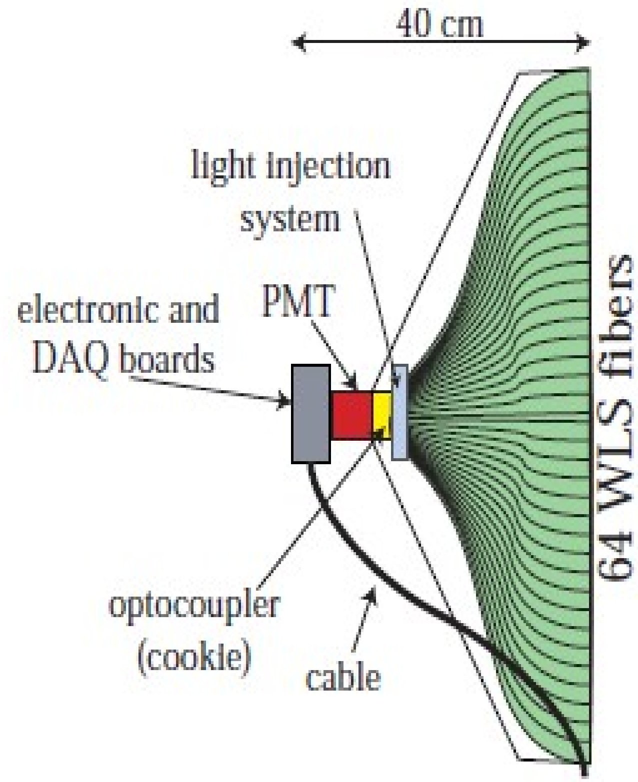
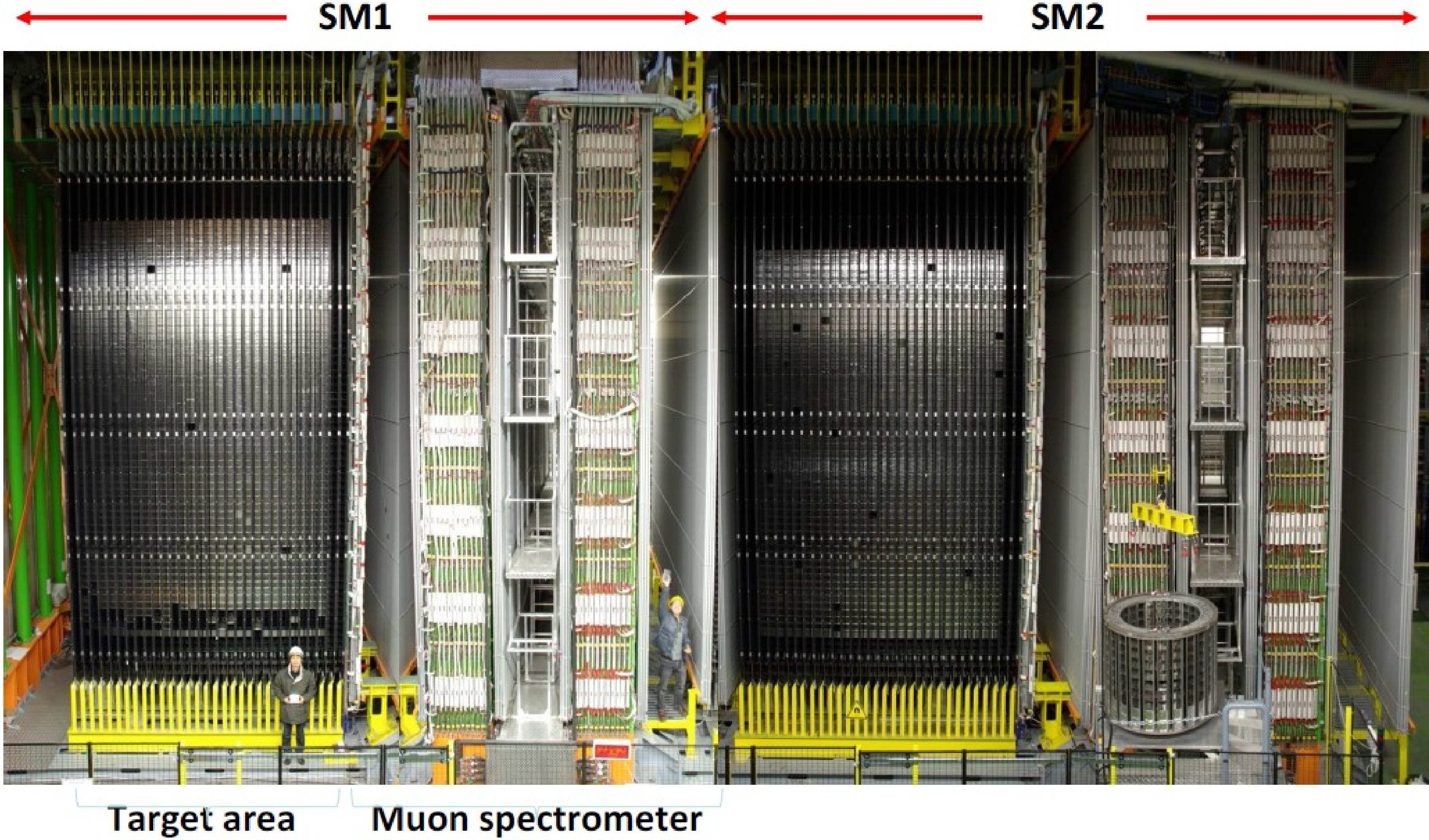


Figure 20. Schematic view of a scintillator strip end-cap with the front-end electronics and DAQ board.

Figure 14. Installation of one OPERA detector Semi-Wall at LNGS.

THE IMPLEMENTATION OF THE PRINCIPLE



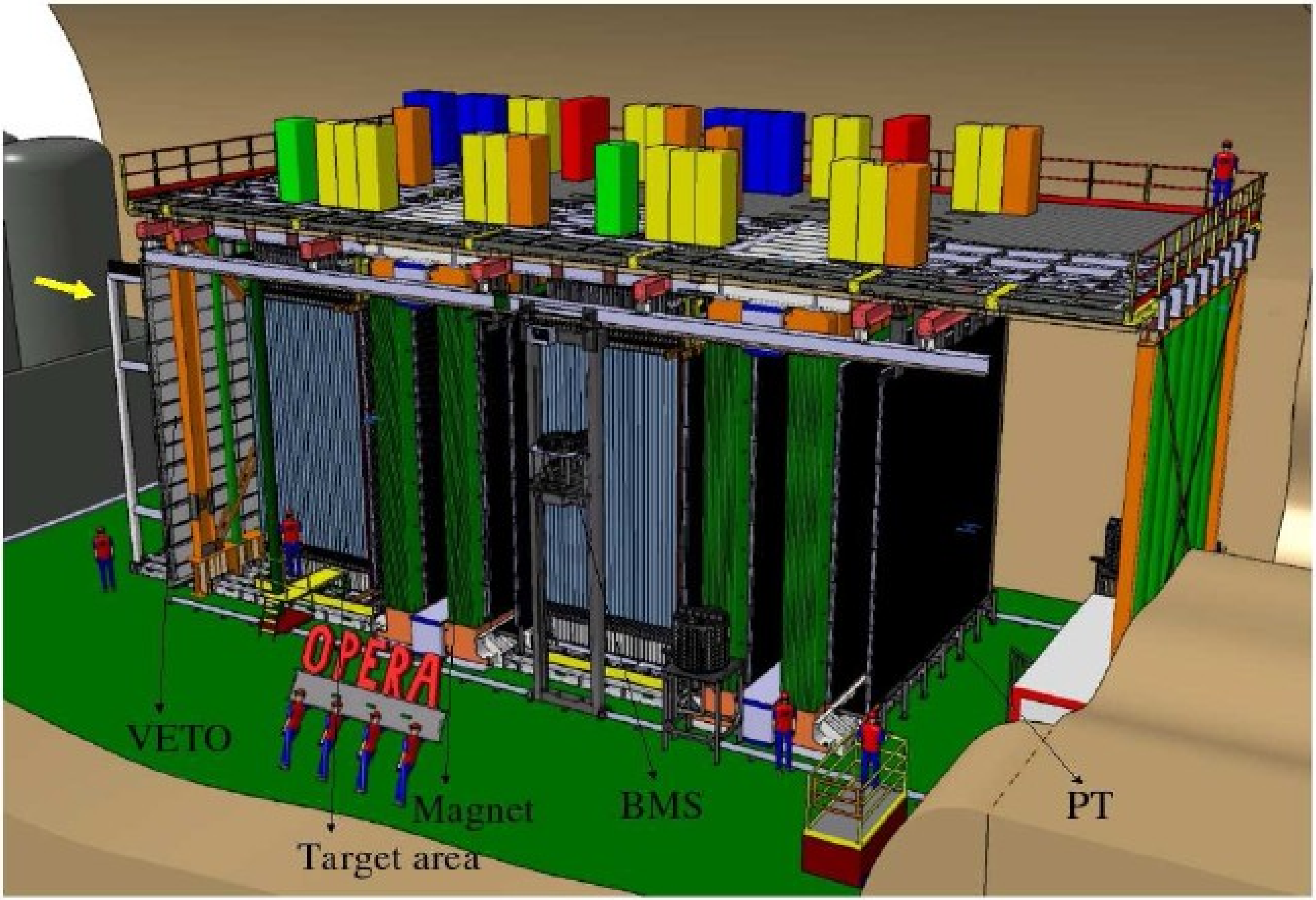


Figure 3. Artistic view of the OPERA detector. The yellow arrow in front of the VETO indicates the direction of the incoming CNGS neutrino beam.

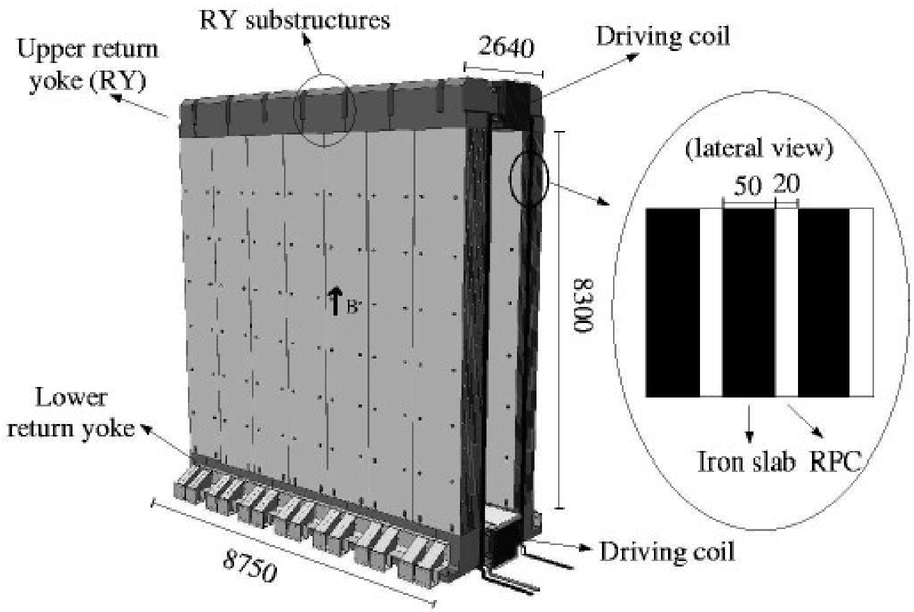


Figure 25. Three dimensional view of one OPERA magnet. Units are in mm. The blow-up insert shows the dimensions of three of the twelve layers of an arm. The height of a slab is given as 8300 mm.

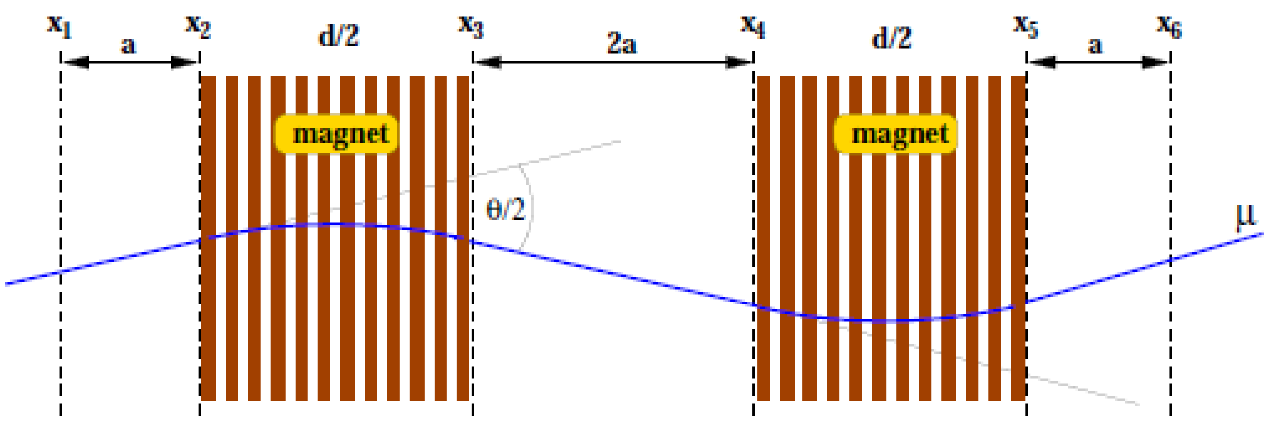
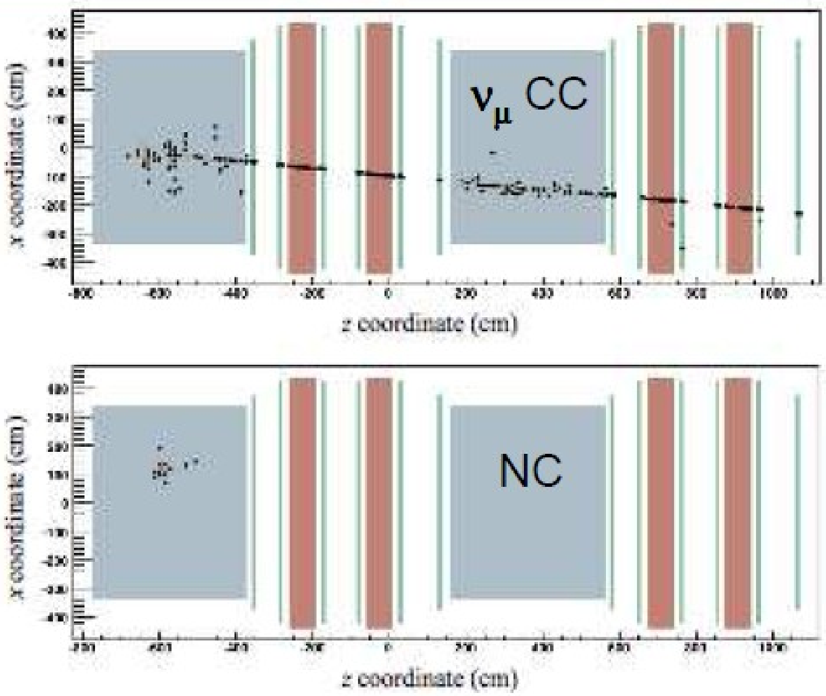
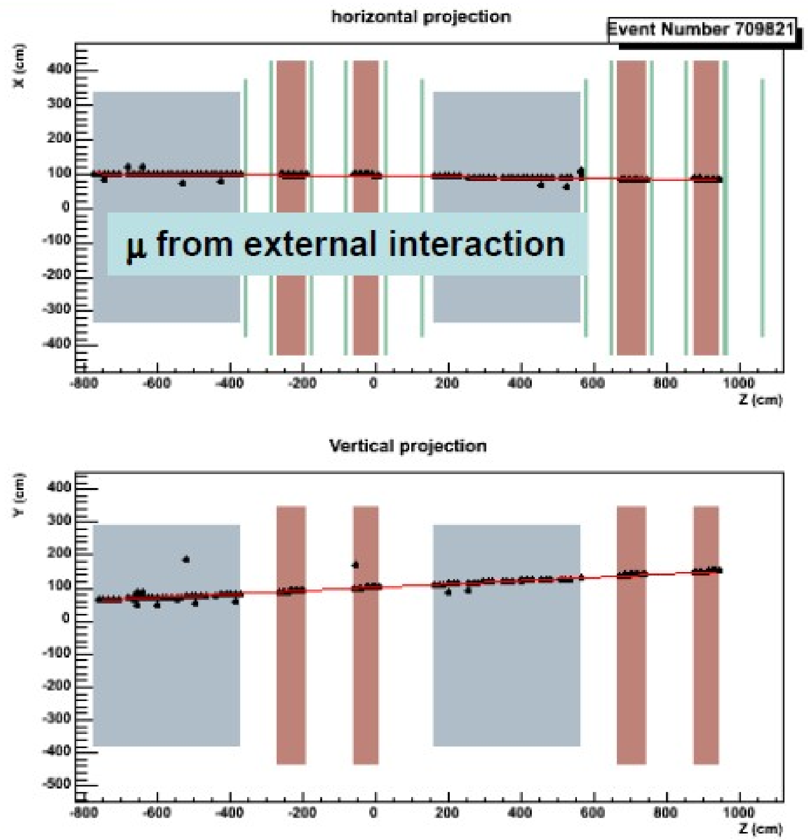


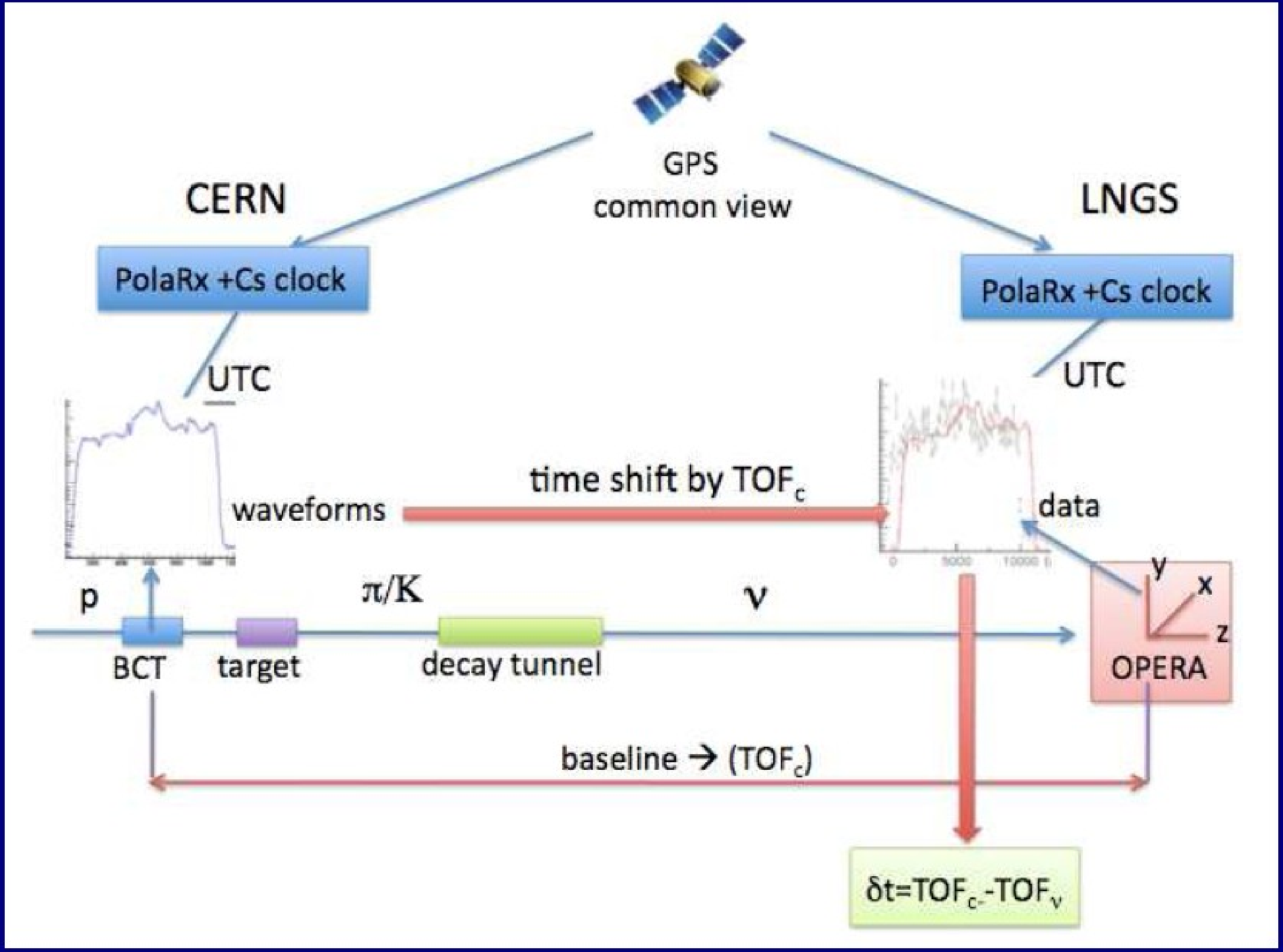
Figure 30. Schematic layout of one half of the muon spectrometer. The six drift tube chambers (PT) are denoted by $x_1 - x_6$. With three chamber pairs the momentum can be extracted from two independent measurements of the deflection of the charged particle in the magnetic field.

“INTERNAL” and “EXTERNAL” OPERA EVENTS





Summary of the principle for the TOF measurement



Measure $\delta t = TOF_c - TOF_\nu$

GPS common-view mode

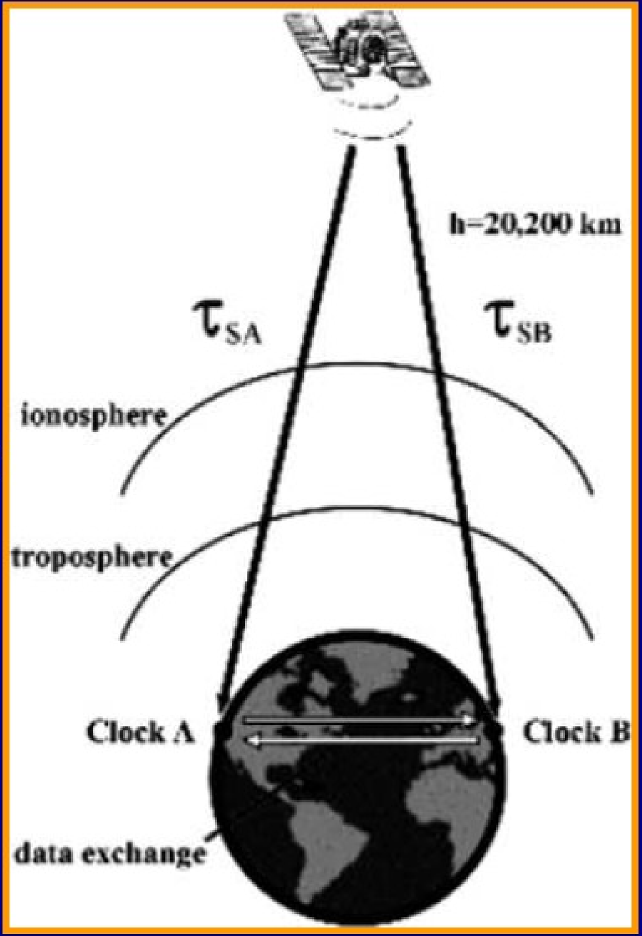
Standard GPS operation:

resolves x, y, z, t with ≥ 4 satellite observations

Common-view mode (the same satellite for the two sites, for each comparison):

x, y, z known from former dedicated measurements: determine time differences of local clocks (both sites) w.r.t. the satellite, by offline data exchange

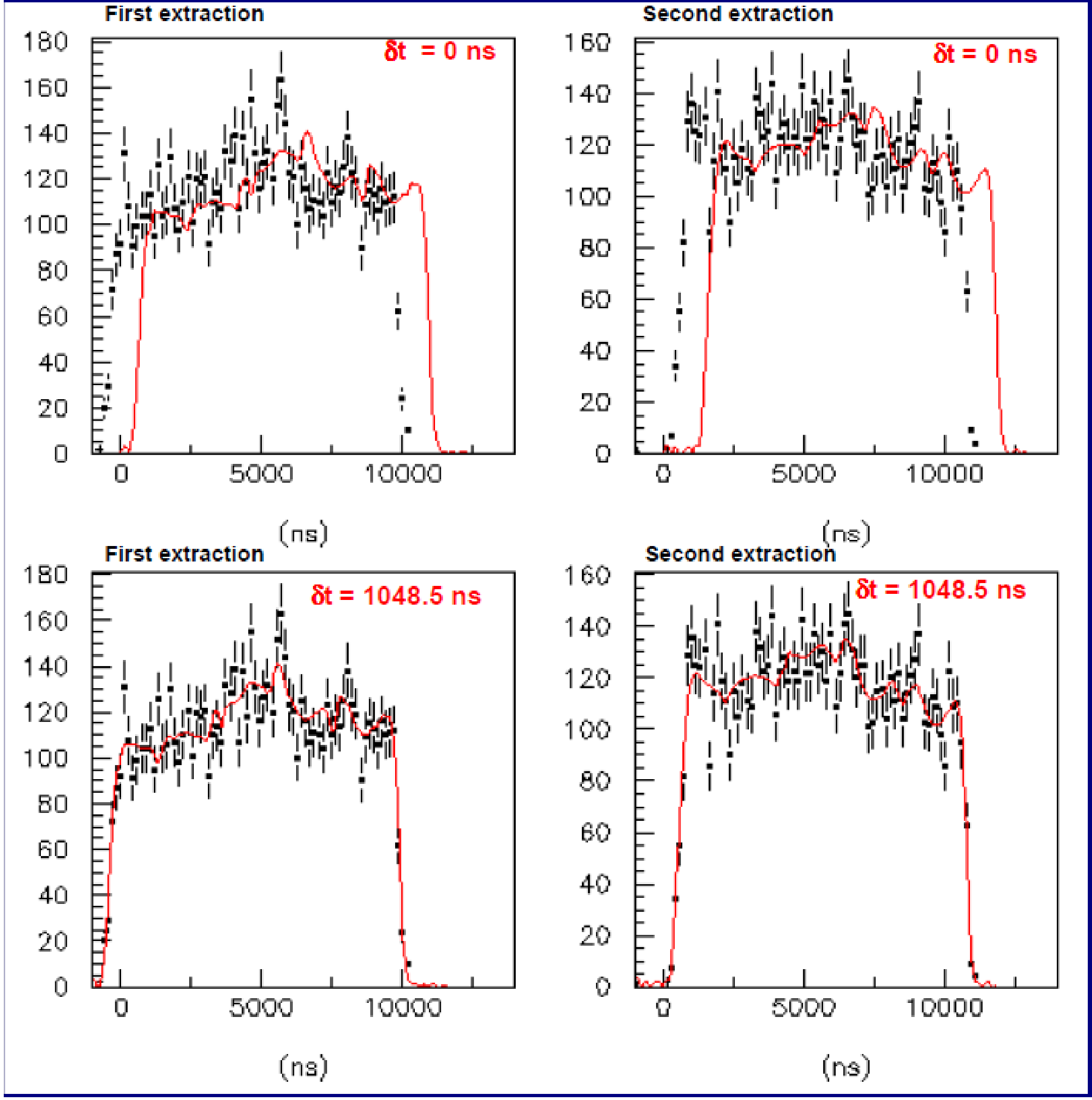
730 km << 20000 km (satellite height) → similar paths in ionosphere



Delay calibrations summary

Item	Result	Method
CERN UTC distribution (GMT)	10085 ± 2 ns	• Portable Cs • Two-ways
WFD trigger	30 ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
LNGS UTC distribution (fibers)	40996 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	4262.9 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement

Data vs PDF: before and after likelihood result



(BLIND) $\delta t = TOF_c - TOF_\nu =$

(1048.5 ± 6.9) ns (stat)

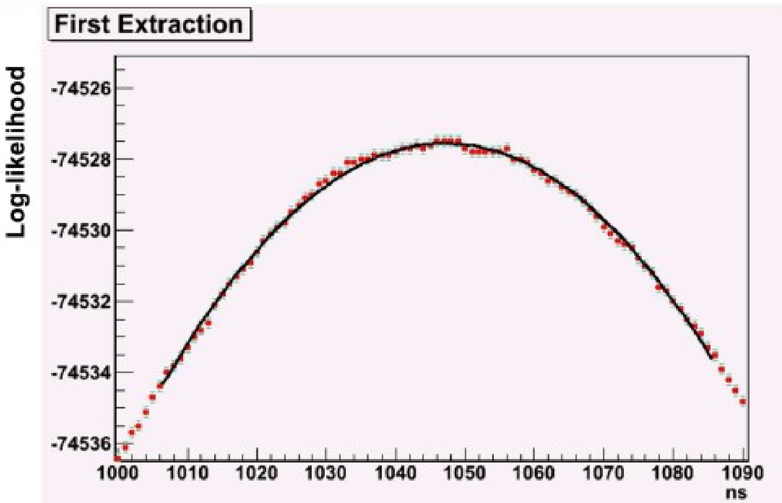
χ^2 / ndof :

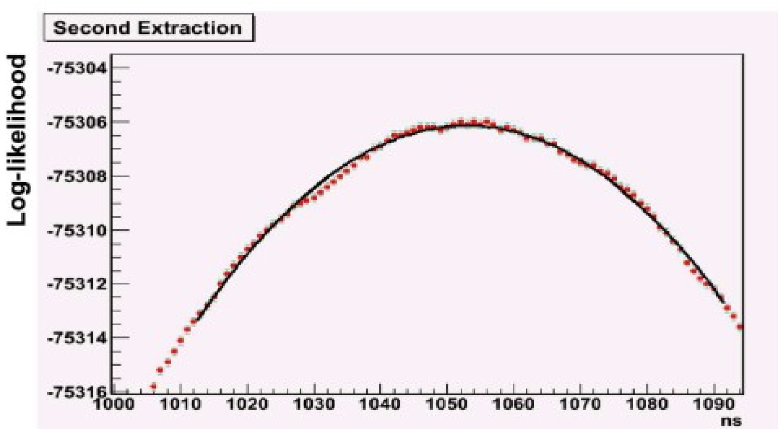
first extraction: 1.06
second extraction: 1.12

Analysis method

For each neutrino event in OPERA → proton extraction waveform

Sum up and normalise: → PDF w(t) → separate likelihood for each extraction





$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \qquad k=1,2 \text{ extractions}$$

Maximised versus δt:

$\delta t = TOF_c - TOF_\nu$

Positive (negative) δt → neutrinos arrive earlier (later) than light

statistical error evaluated from log likelihood curves

Opening the box

timing and baseline corrections

	Blind 2006	Final analysis	Correction (ns)
Baseline (ns)	2440079.6	2439280.9	
Correction baseline			-798.7
CNGS DELAYS :			
UTC calibration (ns)	10092.2	10085	
Correction UTC			-7.2
WFD (ns)	0	30	
Correction WFD			30
BCT (ns)	0	-580	
Correction BCT			-580
OPERA DELAYS :			
TT response (ns)	0	59.6	
FPGA (ns)	0	-24.5	
DAQ clock (ns)	-4245.2	-4262.9	
Correction TT+FPGA+DAQ			17.4
GPS syncronization (ns)	-353	0	
Time-link (ns)	0	-2.3	
Correction GPS			350.7
Total			-987.8

systematic uncertainties

Systematic uncertainties	ns
Baseline (20 cm)	0.67
Decay point	0.2
Interaction point	2
UTC delay	2
LNGS fibres	1
DAQ clock transmission	1
FPGA calibration	1
FWD trigger delay	1
CNGS-OPERA GPS synchronization	1.7
MC simulation (TT timing)	3
TT time response	2.3
BCT calibration	5
Total uncertainty (in quadrature)	7.4

Results

For CNGS ν_μ beam, <E> = 17 GeV:

$\delta t = TOF_c - TOF_\nu =$

(1048.5 ± 6.9 (stat.)) ns – 987.8 ns = (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns

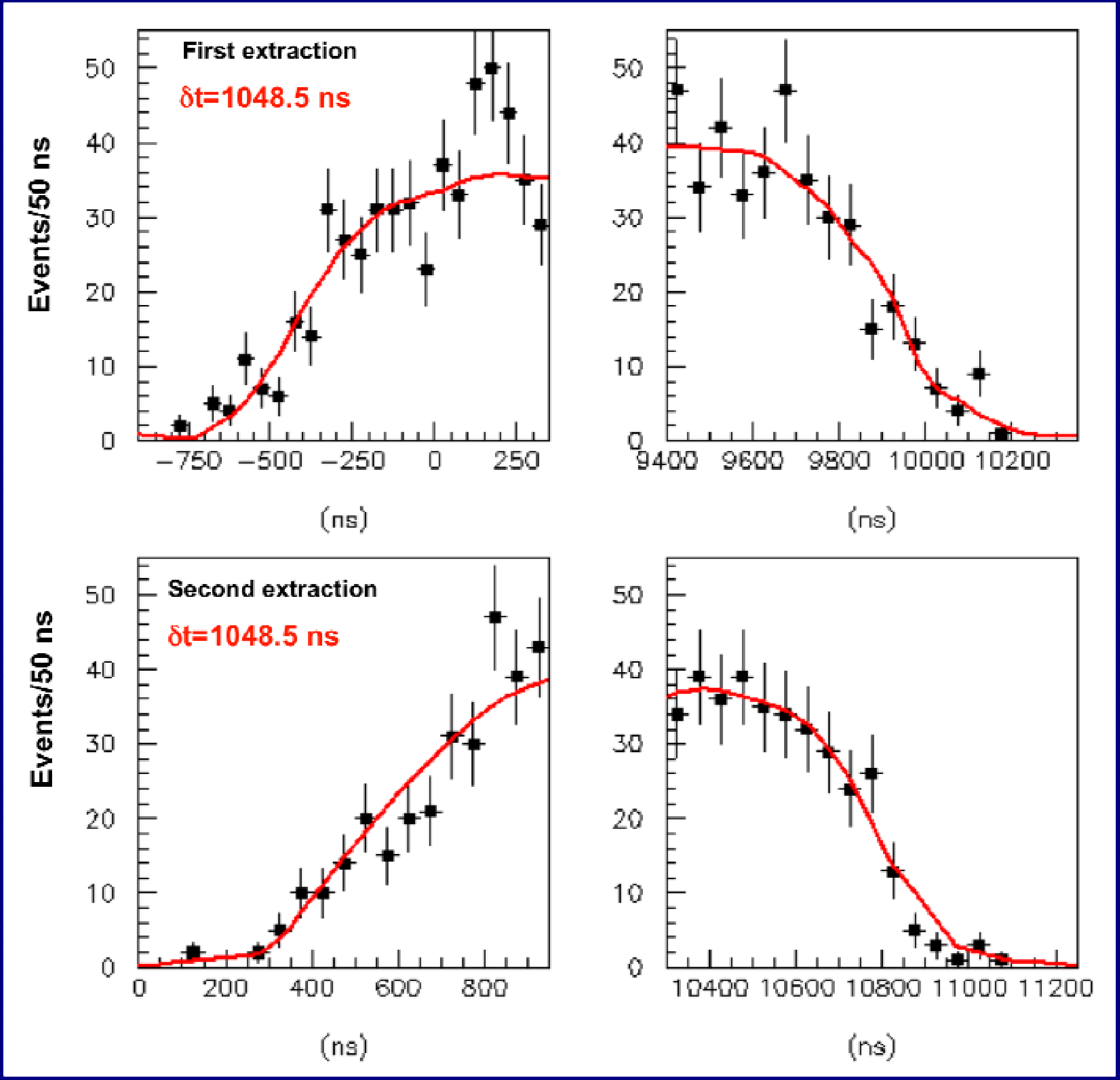
relative difference of neutrino velocity w.r.t. *c:*

$(v-c)/c = \delta t / (TOF_c - \delta t) = (2.49 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$

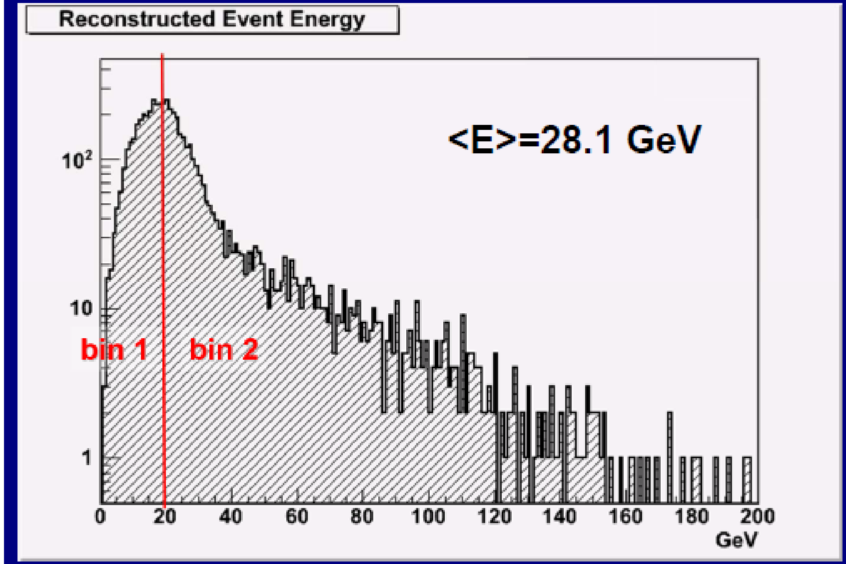
(730085 m used as neutrino baseline from parent mesons average decay point)

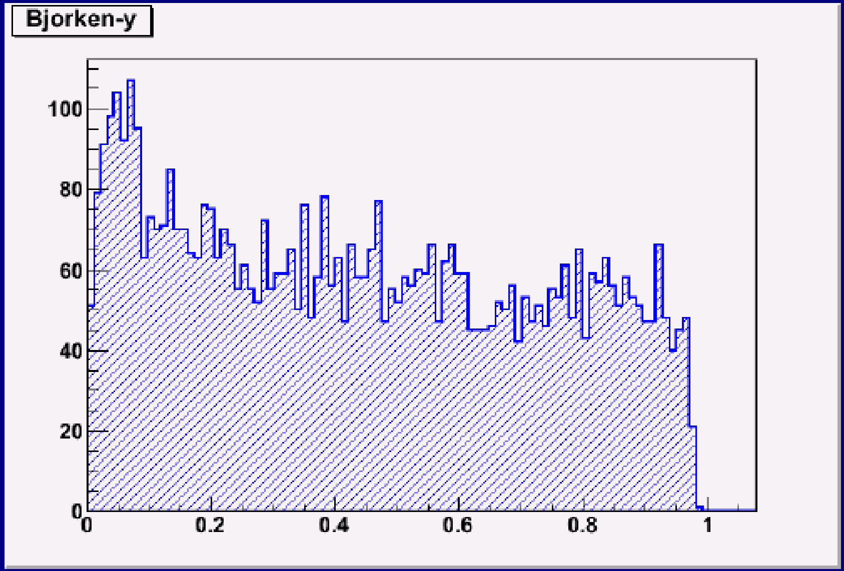
6.0 σ significance

Zoom on the extractions leading and trailing edges



Study of the energy dependence





- Only internal muon-neutrino CC events used for energy measurement (5489 events)

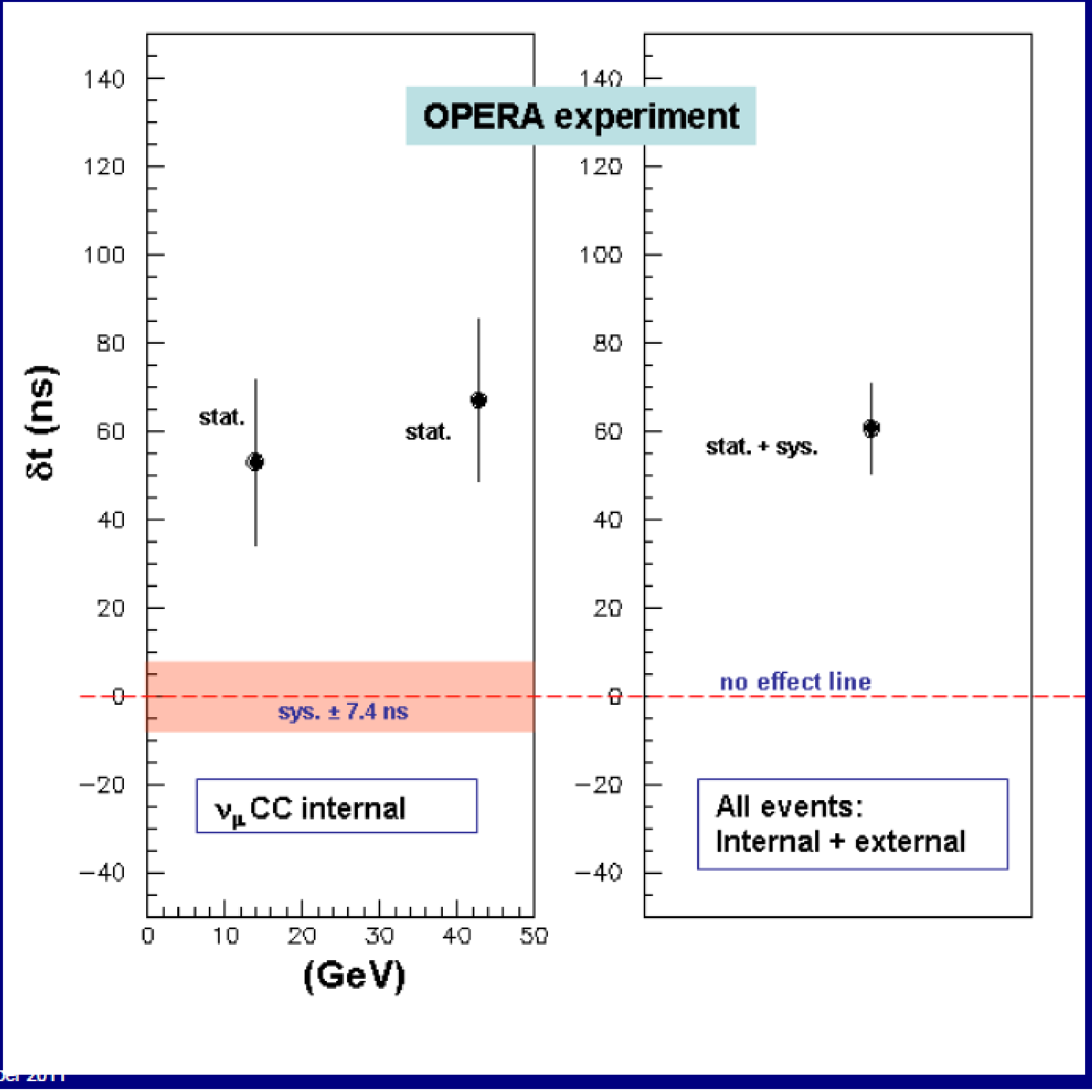
$$(E = E_{\mu} + E_{had})$$

- Full MC simulation: no energy bias in detector time response (<1 ns)
→ systematic errors cancel out

$$\delta t = TOF_c - TOF_\nu = (60.3 \pm 13.1\ (stat.) \pm 7.4\ (sys.))\ ns\ \text{for}\ \langle E_\nu \rangle = 28.1\ GeV$$

(result limited to events with measured energy)

No clues for energy dependence within the present sensitivity in the energy domain explored by the measurement



Conclusions (1)

• The OPERA detector at LNGS in the CERN CNGS muon neutrino beam has allowed the most sensitive terrestrial measurement of the neutrino velocity over a baseline of about 730 km.

• The measurement profited of the large statistics accumulated by OPERA (~16000 events), of a dedicated upgrade of the CNGS and OPERA timing systems, of an accurate geodesy campaign and of a series of calibration measurements conducted with different and complementary techniques.

• The analysis of data from the 2009, 2010 and 2011 CNGS runs was carried out to measure the neutrino time of flight. For CNGS muon neutrinos travelling through the Earth's crust with an average energy of 17 GeV the results of the analysis indicate an early neutrino arrival time with respect to the one computed by assuming the speed of light:

$$\delta t = TOF_c - TOF_\nu = (60.7 \pm 6.9\ (stat.) \pm 7.4\ (sys.))\ ns$$

• We cannot explain the observed effect in terms of known systematic uncertainties. Therefore, the measurement indicates a neutrino velocity higher than the speed of light:

$$(v-c)/c = \delta t\ /(TOF_c - \delta t) = (2.48 \pm 0.28\ (stat.) \pm 0.30\ (sys.)) \times 10^{-5}$$

with an overall significance of 6.0 σ.

Conclusions (2)

• A possible δt energy dependence was also investigated. In the energy domain covered by the CNGS beam and within the statistical accuracy of the measurement we do not observe any significant effect.

• Despite the large significance of the measurement reported here and the stability of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to identify any still unknown systematic effect.

• We do not attempt any theoretical or phenomenological interpretation of the results.

- (v-c)/c = 5.1±2.9 x10-5 FNAL –MINOS
  мюонные нейтрино 3-100 ГэВ

- I v-c I/c < 2x 10-9 Supernova
  электронные антинейтрино ~10 МэВ